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6 REVERBERATION MEASUREMENTS IN WATER TANKS,

by

10 E. L./Klein ~~and~~ D. D./Baker

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The recent trend in antisubmarine warfare (ASW) sonar toward larger transducers which operate below 5 kc has created a calibration problem. For more than 20 years ASW transducer directivity patterns and source levels have been measured by the use of pulse techniques in tanks of moderate dimensions (e.g. 15 ft x 15 ft x 15 ft). These tank measurements (at frequencies above 10 kc) were actually made in the farfield or the Fraunhofer region of the transducer. These existing tanks are not large enough to allow farfield measurements to be made in them with modern ASW transducers, some of which will hardly fit into the tanks.

Since 1959 Defense Research Laboratory has been engaged in the development of a means of predicting farfield transducer characteristics from measurements made in the nearfield (at ranges small compared to the transducer dimensions).¹ Significant progress has been made in this direction. Some recent, successful measurements were made in a highly reflective tank by measuring near the leading edge of the received pulses; i.e., before reflections from the tank walls could cause interference. This tank was 2.9 times the size of the transducer in diameter.

For transducers below 5 kc, nearfield measurements will be made in tanks that may be too small for the leading-edge pulse technique. Under these circumstances, the absorptive properties of the tanks will need to be determined; echo reduction in the tanks will become necessary. This memorandum

¹D. D. Baker, "The Determination of Farfield Characteristics of Large, Low-Frequency Transducers from Nearfield Measurements," Defense Research Laboratory Acoustical Report No. 196, 15 March 1962.

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22 June 1962
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Page 2

presents a preliminary outline of a method of determining tank absorptive properties and of a related method of determining the power output of a transducer in a tank. These are called "reverberation measurements" because both involve measuring the reverberation in the tank. These methods are not yet recommended as practical approaches to the problems but are presented for the benefit of those desiring to make such measurements. It is hoped that the methods will prove to be practical after more research and will serve to supplement DRL's method of predicting farfield directivity patterns and source levels. The methods presented have been used in work done at Stanford Research Institute² and in smaller amounts of work done at other establishments. The few data on tank properties that have been obtained by these methods are presented.

It should be emphasized that the methods presented do not represent established, practical ways in which to make the desired measurements, but only ways that appear to be feasible.

THEORETICAL BACKGROUND

In the outlined methods of determining tank absorption and transducer power output, the theory has been taken from air acoustics.^{3,4,5} The measurement of tank properties closely follows measurement of room properties in architectural acoustics. The measurement of transducer power output closely follows measurement of loudspeaker power output in air.

²V. Salmon, et al, "Prediction of Far Field Performance of Sonar Projectors from Near Field Measurements," Final Report, Stanford Research Institute Project No. SU-3077, November 1961.

³L. L. Beranek, Acoustic Measurements (John Wiley and Sons, New York, 1949) Ch. 7.

⁴L. E. Kinsler and A. R. Frey, Fundamentals of Acoustics (John Wiley and Sons, New York, 1950) pp. 398-403.

⁵C. M. Harris (Editor), Handbook of Noise Control (McGraw-Hill, New York, 1957), Ch. 17.

In air the speakers and microphones have dimensions that are small compared to the wavelength λ . This means that they are not appreciable absorbers and that the speaker is not highly directional. This is one justification for the assumption of uniform average energy density in the room. Throughout the theory, uniform average energy density is assumed and absorption by the transducers is neglected. In air either a warbled tone or a band of noise is used to drive the speaker in order to reduce standing waves in the room. In some instances rotating diffusers are also employed to reduce the standing waves. Because in practice the standing waves cannot be eliminated, uniform average energy density cannot be realized. This necessitates making measurements at several locations in the room and averaging results. Fewer measurements are involved if the locations are carefully chosen according to certain empirical criteria.

The underwater application for the measurement of tank absorption can be made to fit the theory fairly well. Small transducers can be used with warbled frequencies or bands of noise. Careful transducer positioning then gives a situation similar to that found in room measurements. Measurements may be made at several locations and averaged to get good results. The method presented for these measurements has been used successfully in several cases.

In the power output measurement of a transducer, however, it is not always possible to achieve the situation found in room measurements. If one could choose a small transducer to be measured over a noise band, there would be no great problems. In the case of an ASW transducer there are serious problems. These transducers are large enough to be appreciable absorbers and directional enough to give nonuniform average energy density. Furthermore, these transducers are designed for single frequency operation and must be measured in that way. This creates a standing wave problem which cannot be remedied by the use of diffusers since the use of these is impossible in water. The method presented for transducer output measurement has been applied successfully at SRI to a small transducer operated at a warbled frequency. In this test measurements were made at many points in order to get good averaging. This method as presented may not be adequate for use with single-frequency transducers. More work needs to be done in this area.

SUGGESTED MEASUREMENT TECHNIQUES

Measurement of Absorption in a Tank

The actual quantity measured is D, the rate of reverberation decay in the tank. Several absorption parameters can be calculated from D. The method for determining the absorption of a bare tank will be presented first, followed by the method for determining the absorption of absorbent material suspended in a tank.

Bare Tank Absorption

The projector placed in the tank should be as nearly a point source as possible. It should be driven by a band of noise or a warbled frequency. It should be placed away from the boundaries of the water volume by at least its major linear dimension and should not be placed at the center or on any axis of symmetry of the tank. The distances from the projector to all reflecting surfaces should be both unequal and incommensurable.

The hydrophone should also be nearly a point source and should be placed away from the projector by at least the major linear dimension of the projector. It should also be placed at least $\lambda/4$ from the boundaries of the water and at least $\lambda/2$ from edges of the water volume.

The projector should be driven either by a continuous signal that can be cleanly cut off at a certain time or by a pulsed signal of sufficient pulselength that reverberation in the tank ceases to build up before that pulse ends. Either of these modes of operation means that steady-state reverberation is achieved in the tank. The signal from the hydrophone is applied to a logarithmic amplifier the output of which is applied either to an oscilloscope or to a high-speed strip-chart recorder. The signal to the projector is cut off. After the transmission time to the hydrophone elapses, the level out of the hydrophone drops very quickly to the level of pure reverberation in the tank. This reverberation immediately starts to decay. This decay curve should be recorded from the oscilloscope with a camera or on the strip-chart recorder. If a strip-chart recorder is used, it should

be ascertained that it is sufficiently fast since the rates of decay can be as high as about 1000 db/sec. These records should show at least 40 db of decay.

At least five of these decay curves should be recorded at each of about 10 hydrophone positions. Since the theoretical reverberation decay should be exponential, these logarithmic records should follow a straight line. If the decay curves measured either have short term fluctuations or are gently curving in shape, a straight line should be fitted to them. If the curves appear to consist of two straight line segments of different slope, they should be rejected. The slopes of the acceptable decay curves should be measured and averaged logarithmically.⁶ This procedure gives an average value of D in db/sec.

Using the measured value of D, one may compute the average absorption coefficient $\bar{\alpha}$ (the fraction of incident energy absorbed for random incidence) with the formula,

$$\bar{\alpha} = 1 - \exp(-DV/1.085Sc) \quad (1)$$

where V = the volume of water in the tank,
 S = the area of the boundaries of the water volume with the air-water surface excepted, and
 c = the speed of sound in water.

The tank constant R may be computed with the formula

$$R = S \bar{\alpha} / (1 - \bar{\alpha}) \quad (2)$$

The reverberation time of the tank T_{60} is defined by

$$T_{60} = 60/D \quad (3)$$

⁶ Ibid.

The echo reduction for normal incidence (in db) is given by

$$ER = 10 \log_{10} [1/(1-\bar{\alpha})] ; \quad (4)$$

the total absorbing power A (Sabins) is given by

$$A = S \bar{\alpha} . \quad (5)$$

Absorption of Material Placed in the Tank

To determine the absorption due to absorbent material placed in a tank, one must first determine the absorption due to the bare tank as discussed previously. The average value of decay rate is measured and called D_1 (instead of D as before). The absorbent material is suspended in the tank but is not allowed to touch the walls. This restriction stems from the fact that the assumption is made that the tank absorption remains constant and the absorption of the material is added. With the absorbers in the water the entire procedure for measuring decay rate is repeated in order to get a value D_2 for the tank plus absorbers. The average absorption coefficient of the suspended material is given by

$$\bar{\alpha} = (D_2 - D_1) V / 1.085 S_m c \quad (6)$$

where S_m is the area of the absorbent material in the tank.

Measurement of Transducer Power Output in a Tank

Two methods are presented for the determination of the power output of a transducer in a tank. The transducer to be measured is used as the projector. It should be placed according to the previous suggestions for projector placement in tank absorption measurements. Since this projector may well be directional, the main lobe of the beam should not be pointed at the nearest boundary of the water volume and should be slightly inclined with respect to horizontal if possible. Ideally the projector should be driven by a warbled frequency or band of noise. The hydrophone should be positioned as done in tank absorption measurements.

22 June 1962

DDB/gb

Page 7

One of the methods of determining power output involves driving the projector continuously and measuring the average sound power level (SPL) in the reverberant tank. Since energy distribution in the tank, in practice, will not be uniform, values of SPL (in db re 1 μ bar) should be obtained at 10 or 20 positions in the tank and averaged logarithmically. This may need to be done at even more locations if large variations are found. The power output of the transducer L_w (in db re 1 watt) is given by

$$L_w = \underline{SPL} + 10 \log_{10}(S \bar{\alpha}) - 98 \quad (7)$$

The other method of determining power output involves measuring p_r , the sound pressure due only to reverberation. This is measured by transmitting in the way described for tank absorption measurements. The signal to the projector is cut off. Just after the transmission time to the hydrophone elapses, the level is due only to reverberation. This level p_r is measured and is used to compute W (the power in watts) in the formula,

$$W = (p_r^2 S / 4\rho c) [\exp(DV/1.085Sc) - 1] \quad (8)$$

where ρ is the density of water. Values of p_r should be measured at several positions and averaged logarithmically.

RESULTS

The data on tank absorption that have been obtained to date are summarized in Table I. In addition Figs. 1-3 show plots of some reverberation decay curves obtained at NADC. The straight lines chosen to fit these curves are shown also. Figure 4 shows a plot of average absorption coefficient versus frequency for the NADC wooden tank. The data supplied by NADC were so plentiful that it was possible to replot them as shown in the

TABLE I

Establishment and Approximate Date of Test	Tank Description	V Volume in cu. ft.	Type of Measurement	S Wetted Surface in sq. ft.	T ₆₀ Decay Time in Seconds	D Rate of Decay in db/sec	Source Freq.	$\bar{\alpha}$ Absorpt. Coeff.	A- $\bar{\alpha}$ Total Abs.-Pow. Sabins	Remarks
DTMB 1950	3/4" tempered glass in steel frames. Rectan- gular 25' x 8' x 4' 8", Paraffin floor on steel. Water depth 8'. Tank air backed.	932	Bare tank	587	0.012	274	Warbled 4.5 kc	0.08	46.96	D calculated from data supplied in report - very few pertinent tests.
NEL 1961	Reinforced concrete 8" walls, Bottom 4" reinforced concrete set on ground. Rec- tangular 30' x 12' x 7.5'. Water depth 7.5'	1800	Bare tank	780	0.12	510	Noise band at 2 kc	0.2	156	D calculated from data supplied in letter. One test made.
SRI 1961	3/16" steel tank air- backed cylindrical 8' diam. 12' high. Bottom steel on wood resting on concrete. Water depth 11'.	553	Bare tank Bare tank Type-A absorber	326 326 54	0.43 0.17 0.08	140 350 750	Warbled 5 kc 8.8±.4kc (warbled) 8.8±.4kc (warbled)	0.04 0.11 0.76	13.+ 36.- 41.+	
MINS 1961	1/4" steel-rectangular tank 7' x 5' x 5', water depth 4'.	140	Bare tank Type-A absorber	131 18	0.57 0.081	105 740	Noise between 1.7-9.6 kc	0.02 0.92	2.62 17.56	
MADC 1961	White cedar 3" staves, cylindrical, diam. 20', height 15', water depth 12.25'.	3847	Bare tank Bare tank Bare tank	1084 1084 1084	0.41 0.10 0.065	147 600 917	Noise band: at 1 kc at 2.5 kc at 5 kc	0.09 0.33 0.46	97.56 357.72 498.64	D calculated from replotted curves. See Figs. 1, 2, 3, 4.
NRL 1962	6' x 15' x 7.5' concrete 8" painted walls	675	Bare tank	405	0.057	1054	Averaged results for noise bands at 9 frequencies between 0.2 and 5.0 kc	0.28	113.3	
GD/E-R 1962	Cylindrical steel, diameter 48', height 30'. Bottom 10' sand- backed; the rest air- backed. Lower 8' has 11/32" wall. Top 22' and bottom are 1/4".	52,470	Bare tank	6182	0.4 0.75 1.5 1.9	150 80 40 25.5	Noise band: at 0.1 kc at 1.0 kc at 10 kc at 25 kc	0.21 0.18 0.06 0.049	1300 1100 370 300	

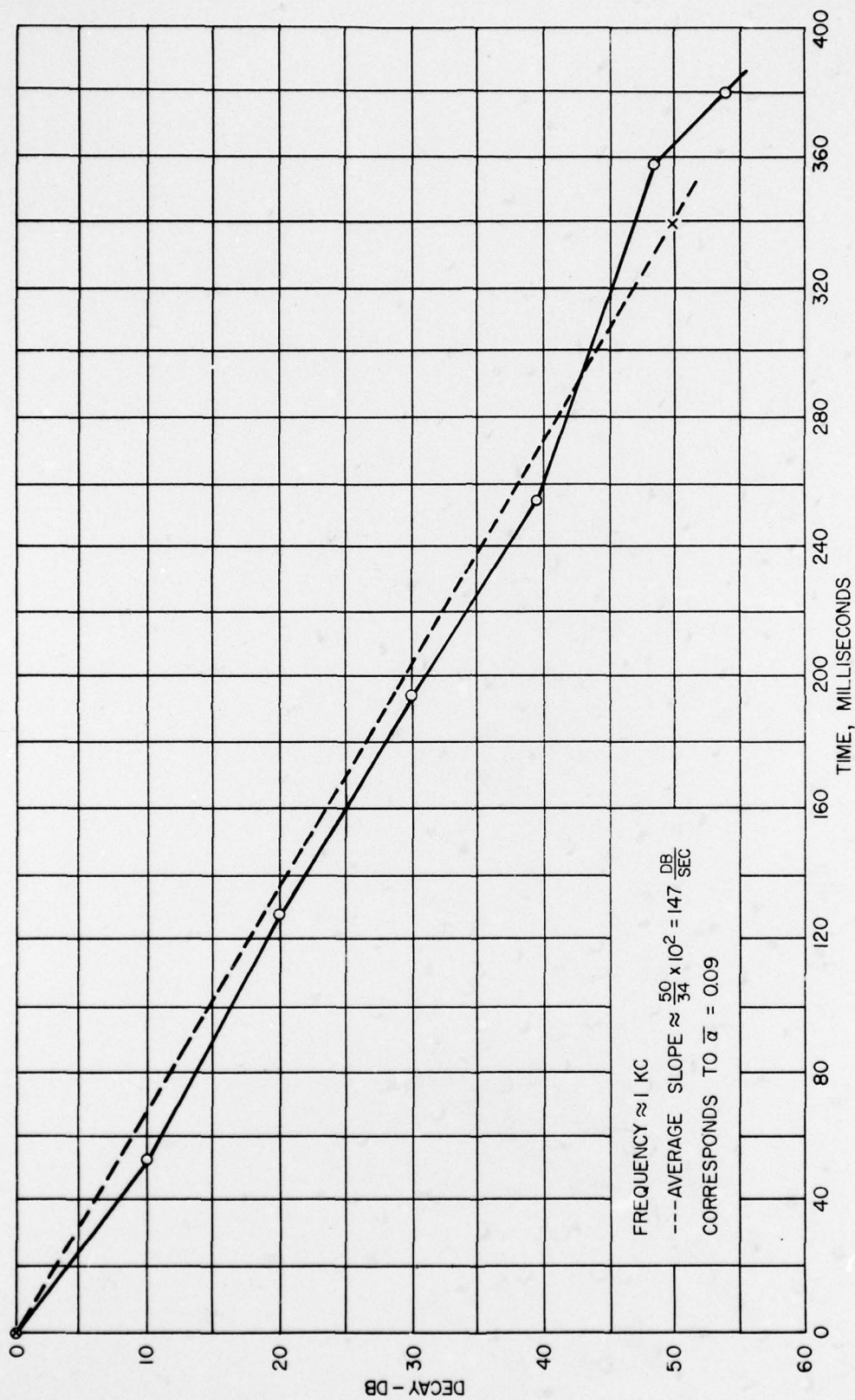


FIGURE 1
 USNADC REVERBERATION DECAY CURVE
 ASWL TANK 1

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 DWG AS 6626
 SWS - BWS
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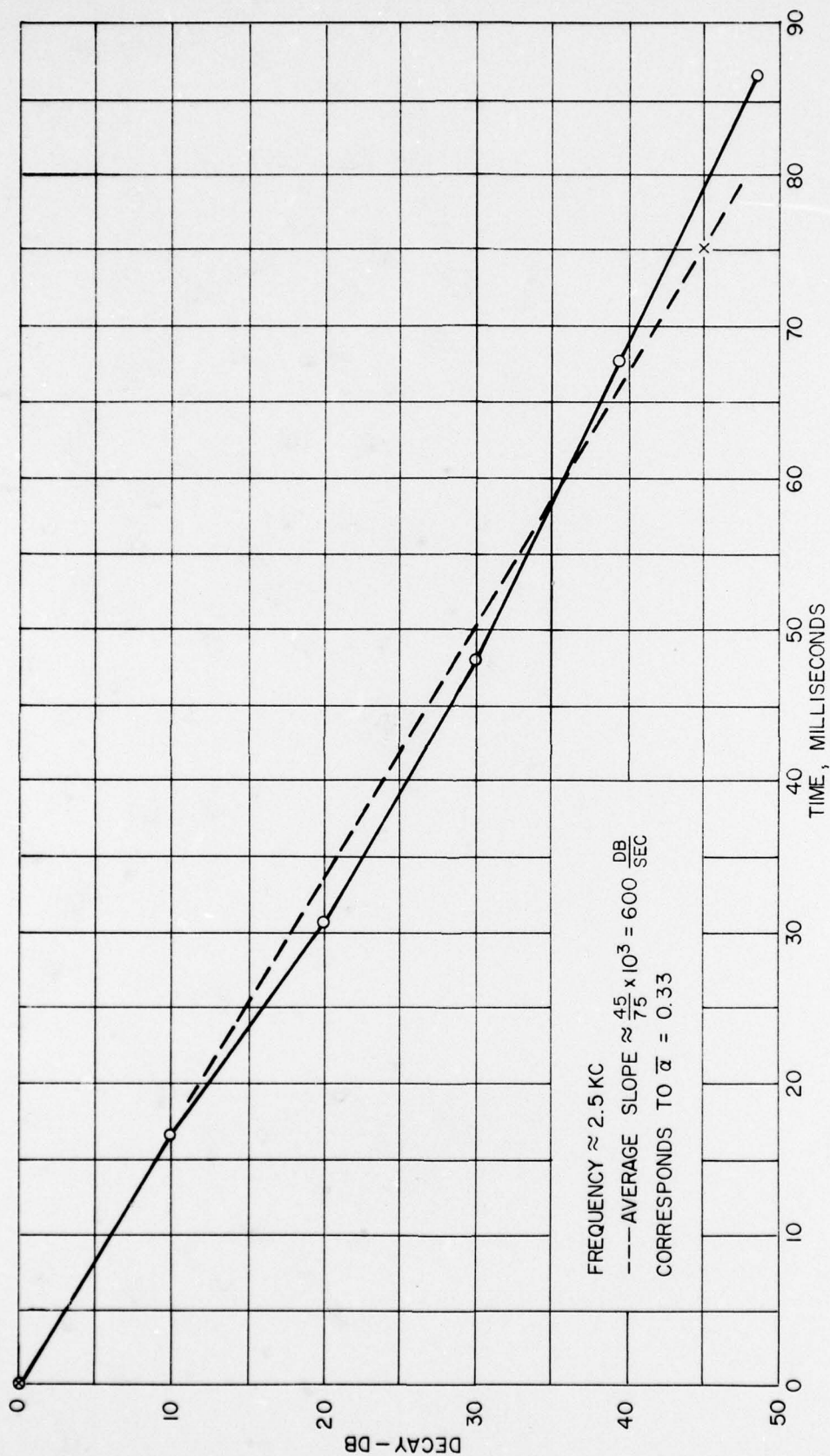


FIGURE 2
 USNADC REVERBERATION DECAY CURVE
 ASWL TANK 1

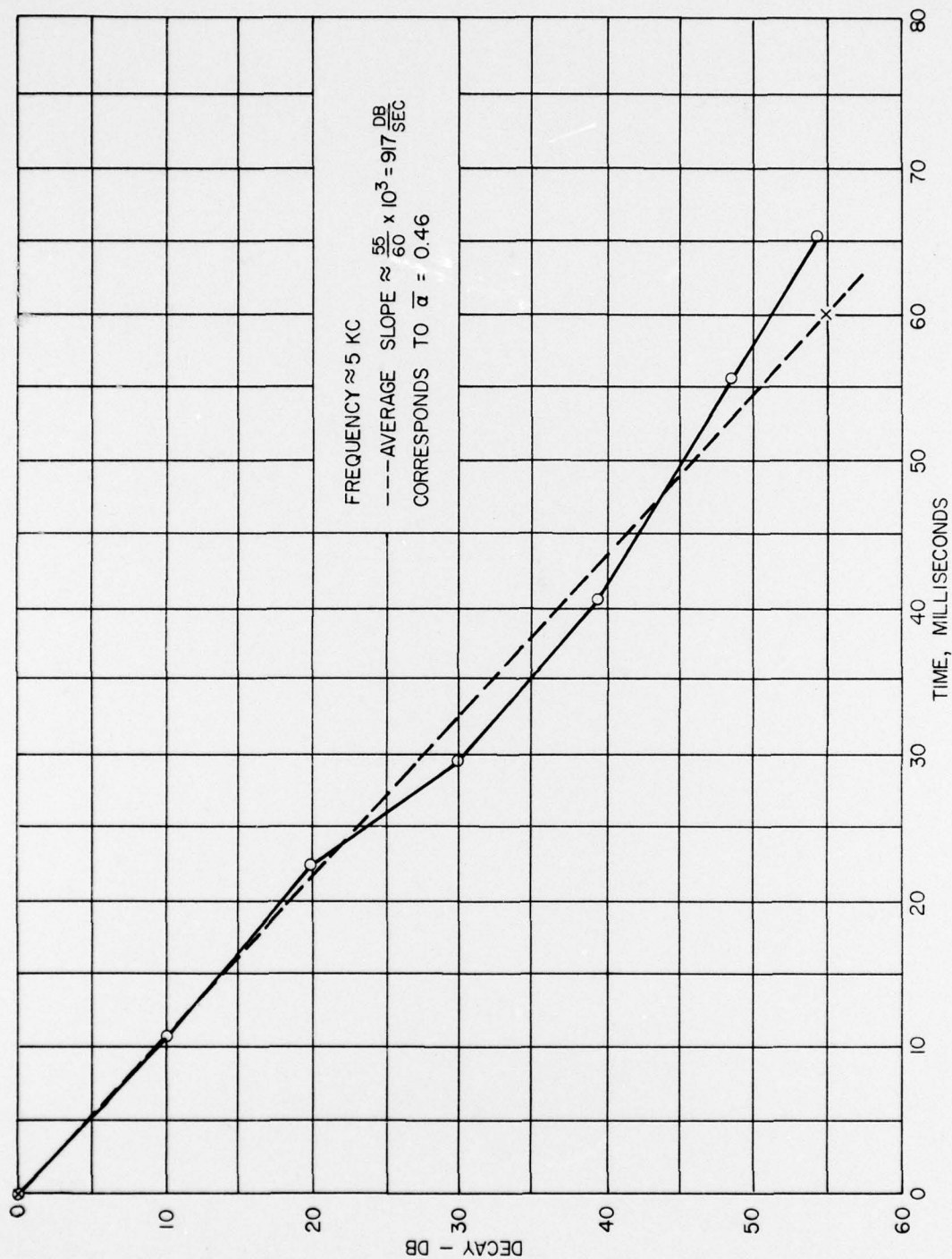


FIGURE 3
 USNADC REVERBERATION DECAY CURVE
 ASWL TANK 1

DRL - UT
 DWG AS 6628
 DDB - BWS
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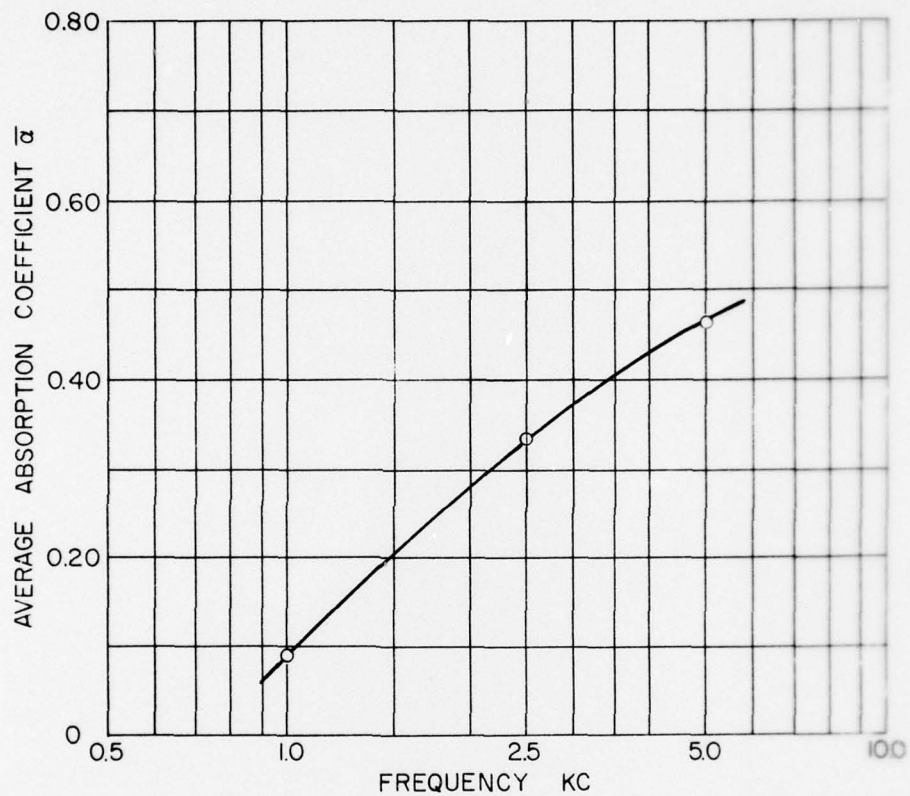


FIGURE 4
AVERAGE ABSORPTION COEFFICIENT α VERSUS FREQUENCY
USNADC ASWL TANK I

DRL - UT
DWG AS 6629
DOB - BWS
3 - 21 - 62

figures. There have been reports issued on some of the measurements summarized in Table I.^{7,8,9}

It may be seen from the table that the steel tanks and the glass tank absorb only a few percent of the incident energy in the vicinity of 5 kc while the concrete tanks absorb about 20 percent. The NADC wooden tank absorbed about 40 percent in the same frequency range. While these values are far from definite, the consistency of the data for the types of tanks is good.

As mentioned previously, transducer power output measurements have been made on a transducer at SRI.¹⁰ The power determined in this way agreed with the known value to within 1 db.

SUMMARY

Methods of measuring tank absorption and transducer power output are presented as guide lines for persons interested in making such measurements. The methods are not established, practical ones, but are tentative. The method for measuring absorption has been tried successfully by several persons. The method of power output measurement has been tried once and was successful. However, the transducer was not one of the large ASW transducers for which this measurement may be important.

The few data available on tank absorption show that wooden tanks absorb nearly one-half the incident energy at about 5 kc. Concrete tanks absorb about 20 percent, and steel ones absorb less than 10 percent.

⁷V. Salmon, et al., op. cit.

⁸F. D. Mattison and W. C. Diehl, "Determination of the Absorption Coefficient of a Concrete Tank," Branch Report No. T-94-R-5, Techniques Branch, Sound Division, U. S. Naval Research Laboratory, March 1962.

⁹D. E. Nelson, "Sonar Tank Reverberation," 95-1095, Research Department, General Dynamics/Electronics-Rochester, 9 March 1962.

¹⁰V. Salmon, et al., op. cit.